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Grattan, John

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Pollution and paradigms: lessons from Icelandic volcanism for continental flood basalt studies

John Grattan*

*The Institute of Geography and Earth sciences, the University of Wales Aberystwyth.

Abstract

This paper is based on the premise that research into the environmental impact of continental flood basalt (CFB) volcanism has paid insufficient attention to the potential ecosystem damage that would result from the direct deposition of hundreds of megatons (Tg) of sulphur and other volatiles. The environmental impacts of the 1783 Laki Fissure eruption are reviewed in outline. It is shown that in a relatively brief period of volcanic activity, volatiles emitted by the eruption damaged and destroyed vegetation from the Arctic Ocean to the Mediterranean. Air pollution was so intense that human health was affected and the national death rate increased dramatically in both England and France.

It is proposed that the events of 1783 may be used as a paradigm for the environmental impacts of a CFB lava flow, and the emissions of 1783 are scaled up to illustrate this point. Thus, if a Laki style event were to erupt for a year it would approach the physical scale of a single episode of the Roza flow in the Columbia River CFB and potentially yield 576 Tg of sulphur gases which could have been oxidised into approximately 945 Tg of aerosol. This could generate a tropospheric aerosol mass of approximately 708 Tg H_2SO_4. The ecosystem impact of the deposition of acids on this scale would be profound and, as with the actual Laki event, be continental in scale. All parts of the plant life cycle would be disrupted, including photosynthesis and fruiting. Inevitably, withthe disruption of food webs animals would also be affected. Poorly buffered inland waters would be acidified, as would Boreal soils, reducing their biodiversity. In our already polluted and interdependent world, any future event on this scale would have serious consequences for human health and trade.

Keywords: Pollution; Paradigm; Continental flood basalt

1. Introduction

Continental flood basalt (CFB) eruptions are plausibly correlated with a number of the extinction events apparent in the palaeontological record (Courtillot, 1999; Wignall, 2001), which has prompted questions as to the mechanisms by which volcanic activity of this style may be able to critically stress and modify environments. Inevitably, global cooling by volcanic aerosols is the mechanism that has received attention, but the geological record frequently indicates increases in the volume of carbon dioxide in the atmosphere at these times (Wignall, 2001), which may be opposing evidence for the operation of a cooling mechanism over the long term. By studying the environmental effects associated with recent Icelandic fissure volcanism, which is the closest current analogue for CFB activity, it may be possible to gain a better understanding of the environmental impacts of CFB volcanism. In this paper, the environmental impacts of the 1783 AD Laki Fissure eruption will be briefly reviewed, followed by consideration of the potential consequences should the peak output of this event been sustained for a year.

2. Laki Fissure eruption

By studying the environmental impacts of the this eruption, which are reviewed in outline below, we may be able to gain insights into the range of environmental mechanisms that could have been affected by CFB episodes and be able to construct more effective models, which relate CFB episodes to mass extinction events. For a few weeks of its 7-month life, the output of the AD 1783–1784 Laki Fissure eruption approached the scale of a single episode of a CFB eruption (Thordarson and Self, 1996). The environmental impacts of the eruption were amongst the most severe of the Holocene, and are noteworthy for the dry fog (Fig. 1) and acid damage observed across Europe (Grattan and Charman, 1994; Grattan and Pyatt, 1999; Swinden, 2001; Thordarson and Self, 2001, 2003), the anomalously hot weather experienced in Europe during the summer of 1783 (Grattan and Sadler, 1999, 2001; Sadler and Grattan, 1999) and the cool summers and cold winters of the years after the eruption ceased (Figs. 2 and 3).

Thordarson and Self (2003) have studied the dynamics of the Laki eruption thoroughly, and the reader is referred to their most recent paper for a detailed account of the eruption. Drawing on this paper, key details may be established: the eruption

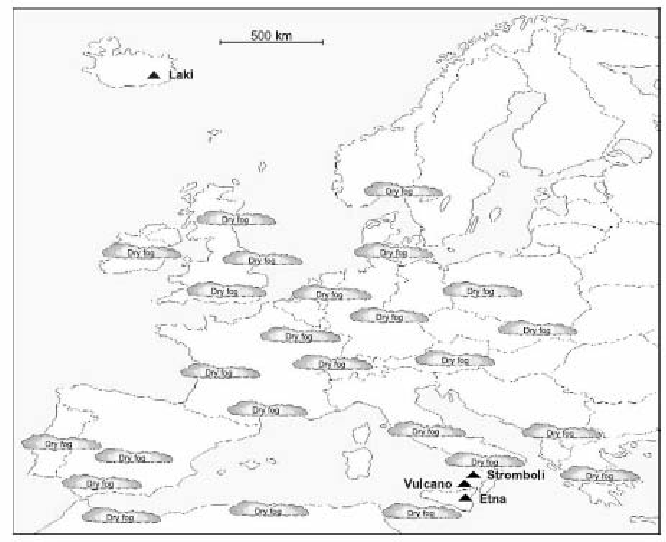

Fig. 1. Extent of the Dry Fog in 1783.

began on June 8th 1783 and ceased on February 7th 1784; it emitted 15.1 km^3 lava and emitted approximately 122 megatons (Tg) SO_2 into the atmosphere. These gases were oxidised by reaction with water vapour in the atmosphere to approximately 200 Tg H_2SO_4 aerosol (Thordarson and Self, 2003). Of these aerosols, 75% were confined to the troposphere with the remainder injected into the stratosphere. Output over this period was uneven, with approximately 80 Tg of SO_2 released in the first 50 days of the eruption (Thordarson and Self, 2003; Thordarson et al., 2003).

Fig. 3. Central England temperature record: July mean temperatures (dotted line: 1770–1795 mean).

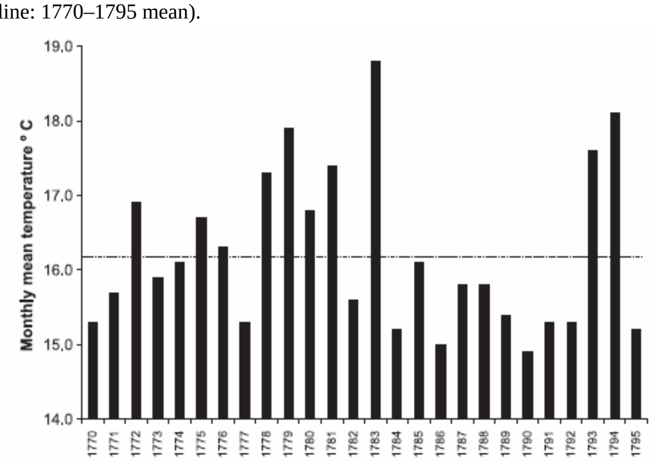

Fig. 3. Central England temperature record: July mean temperatures (dotted line: 1770–1795 mean).

Fig. 2. Central England temperature record: Winter (Dec–Feb) mean temperatures (dotted line: 1770–1795 mean).

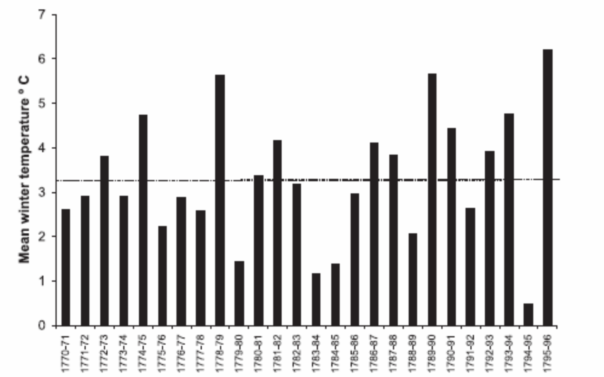

Fig. 2. Central England temperature record: Winter (Dec–Feb) mean temperatures (dotted line: 1770–1795 mean).

3. Environmental impacts of the Laki Fissure Eruption

In Iceland, the environmental impacts of the emitted gases were severe. Farmland was abandoned, crops and pasture were destroyed, mainly by sulphuric acid deposition and both people and livestock appear to have died through a combination of acid deposition, fluorosis, disease and starvation (Tho´ rarinsson, 1969; Ogilvie, 1986; Steingrimson, 1998; Thordarsson, 2003a,b). The experience of Iceland in 1783 and the suffering the people endured in the years that followed, serve to illustrate how powerful the impact of volcanic gases can be in areas relatively close to the volcanic source.

The most obvious manifestation of the Laki eruption away from Iceland was a persistent, foul smelling a˜ dry foga˜ , composed of the gases and derived aerosols emitted by the eruption. The dry fog was reported from Scandinavia to Portugal and from Britain to the Middle East, and even in North America (Fig. 1; Thordarson et al., 1995, 1996; Stothers, 1996; Demare´e et al., 1998; Thordarson and Self, 1993, 2003). The huge area affected by the dry fog in 1783 demonstrates that gases emitted by fissure eruptions can be transported for great distances through the atmosphere and retain sufficient concentration to have a severe environmental impact.

In all the contemporary literature, descriptions of the fog were closely associated with reports of extreme weather and environmental phenomena that are now recognised as symptomatic of the impact of mainly acid aerosols (see Grattan, 1998; Thordarson and Self, 2003 and references therein).

3.1. Climate and weather

In the Northern Hemisphere, the Laki eruption is recognised as having had a considerable climatic impact (Sigurdsson, 1982, 1990; Angell and Korshover, 1985). Current estimates suggest that for 2–3 years the average surface temperature reduction across Europe and North America was N1.3 8C (Thordarson and Self, 2003). The winter preceding the eruption was cold and the further temperature reduction probably induced by the volcanic aerosols resulted in the notably cold winters of 1783–1784 and 1784–1785 and several cool summers in the years 1784–1792, which are illustrated in the central England temperature record (Figs. 2 and 3). Environmentally, the most significant climate impact of the Laki Fissure eruption may not be the harsh winters, but rather the string of cooler than average summers that followed. A consistent reduction of summer temperatures may also reduce the ability of seeds and fruits to ripen and hence germinate successfully. Such a consistent temperature reduction may reduce the latitudinal and altitudinal range of many plants and inevitably affect the animals that exploit them.

In addition to the long-term cooling, in the short term, during the summer months of 1783, exceptionally high surface air temperatures were occasionally recorded in Europe (Kington, 1980), particularly in the month of July. In England, the average daily temperature for July 1783 was 18.8 8C, which was 2.7 8C above the mean for the entire 18th century (Fig. 3), a temperature not equalled until 1983 (Manley, 1974; Kington, 1980; Wood, 1984, 1992; Grattan and Sadler, 2001). Eighteenth century documents, which link the intense stifling heat and the sulphurous stench of the air, are very common. Several authors have now suggested that these excessive temperatures are the result of greenhouse warming processes occurring as a result of the high concentrations of sulphur dioxide in the troposphere (Rampino et al., 1995; Grattan and Sadler, 1999; Grainger and Highwood, 2003), but the process that caused the warming is still imprecisely understood (Thordarson and Self, 2003).

3.2. Damage to plants

The damage described across a wide area of Europe was entirely typical of a modern severe air pollution event, albeit on a scale greater than any anthropogenic incident both in terms of the duration of the air pollution and the physical extent of the area affected. At the onset of the event, the landscape in the Netherlands was described as having ban aspect of desolationQ (Swinden, 1786, republished, 2001). In eastern England, Cullum, in Grattan and Charman (1994), explained that damaged vegetables bappeared exactly as if a fire had been lighted near them, that had shrivelled and discoloured their leavesQ. Descriptions of the damage to vegetation typically emphasised scorching, burning, withering, drying, and a wide range of colour changes. Descriptions of leaf fall were common and plants shed their fruit unripened. The disappearance of wild flowers was also noted in many areas and in addition, seed cases of cereal crops were described as being empty when examined (Rabartin and Rocher, 1993; Grattan and Pyatt, 1999; Demare´e and Ogilvie, 2001).

Acid aerosol damage in Britain, was noted in a wide range of cereal crops, including wheat, barley, and oats, plus a wide range of trees, including the larch, the walnut and various pine trees (Grattan and Charman, 1994). Fish kills were also noted in Scotland (Grattan and Pyatt, 1994, 1999). In Germany, widely reported newspaper articles describe trees shedding their leaves (Grattan, 1998; Grattan et al., 1998; Demare´e and Ogilvie, 2001). In central Germany, the air was described as being full of sulphur killing everything in the woods (Grattan et al., 2000). Across Scandinavia, acid rain, gases and aerosols were reported as having damaged cereal crops whilst in Bergen, where it was reported that they could smell sulphur in the air, and both plants and animals died and famine ensued (Tho´rarinsson, 1979, 1981; Demare´e and Ogilvie, 2001).

In France, the correspondence discovered to date often describes premature leaf fall and scorching of leaves (Stothers, 1996; Grattan et al., 1998, 2002), but here most of the emphasis was on the damage caused to cereal crops in the Loiret region. Famine and agricultural depression ensued and continued for several years into the French Revolution (Rabartin and Rocher, 1993; Grattan et al., 1998). Camuffo and Enzi (1995) reported acid damage to vegetation in northern Italy, whilst Demare´e and Ogilvie (2001) also note damage to plants in Romania, Slovakia and Hungary. It seems likely that future detailed research will reveal further evidence of the impact of the sulphurous fog.

One account of plant damage in 1783 was particularly detailed and worth reviewing here as it reveals wide ranging damage to the plant kingdom. When the Dutch scientist Brugmans (1787) observed the damage caused to plants near his home, he travelled to the Botanical Garden of the University of Gro¨ningen in an attempt to more fully understand the sulphurous fog and its impact; his study is a valuable indicator of the intensity of the impact of the event. He listed the damaged plants he observed there in four categories, from the most severely damaged to those barely affected. The full list of plants affected is too long to reproduce here but amongst the plants severely affected are listed an extensive range of wild flowers and common grasses; trees and shrubs including hazel, laburnum, walnut, pine, cedar, fir, willow, birch, beech, chestnut, pear, apple and poplar; fruiting plants such as redcurrant, blackcurrant, raspberry and blackberry; a wide range of beans;

and cereals including oats, barley, hop and buckwheat. These data, taken together, indicate that few plant species in Europe were immune to the impact of the Laki aerosols. Furthermore, they suggest that a wide range of critical plant processes were affected including, photosynthesis, leaf formation, leaf retention, fruiting, flowering and seeding. The range of damage described suggests that the pH of the aerosol may have been b2.0.

3.3. Human health

Not surprisingly, the intensity of the air pollution caused ill-health and common references were made to general sickness, dysentery, difficulty in breathing, asthma, sore eyes, headaches, sore throats; tingling hands, lips and eyes (Stothers, 1996; Brayshay and Grattan, 1999; Durand and Grattan, 1999, 2001; Demare´e and Ogilvie, 2001; Grattan and Durand, 2002;). In modern air pollution incidents, these symptoms may be induced at sulphur dioxide concentrations between 150 and 3000 cg/m^3 depending on duration of the exposure (Ostro et al., 1991; Brauer et al., 1995; Goldsmith et al., 1996).

3.4. Mortality

Ongoing research now point to high levels of human mortality in Europe in 1783. High levels of mortality, coincident with volcanic activity, have been noted before, with plague and other pandemics being identified as the most probable cause; volcanic modification of climate creating conditions that encourage the more efficient operation of disease vectors (Stothers, 1999, 2000). In 1783, environmental conditions more closely resemble contemporary air pollution incidents. In modern air pollution incidents, where high air temperatures and poor air quality act in combination, people die in considerable numbers. The victims are commonly the young, the old and the sick (Dockery et al., 1992; Katsouyanni et al., 1993; Durand and Grattan, 1999, 2001). Recent work (Grattan et al., 2003a,b) has indicated that in addition to the known deaths in Iceland, where a quarter of the population ultimately perished, high rates of mortality also occurred in England and France (Fig. 4A and B). The mortality in Iceland was caused by a combination of exposure to the volcanic gases, famine and disease. Elsewhere in Europe, excessive deaths were frequently associated with the presence of the dry fog (Rabartin and Rocher, 1993; Grattan et al., 2003a,b). In England, the national death rate was doubled and in France the death rate may have been as high as 5% of the population (Demare´e and Ogilvie, 2001; Grattan et al., 2001, 2002, 2003a,b; Witham and Oppenheimer, in press). The cause of the excess mortality in 1783–1784 has yet to be determined, but a consensus may form around a synergistic mechanism that combines air pollution, contamination of water supplies and extreme summer and winter temperatures. What is clear is that the synchronous excess mortality occurred from the summer of 1783 to spring 1784 in both England and France, which suggests the existence of an overarching vector, or vectors.

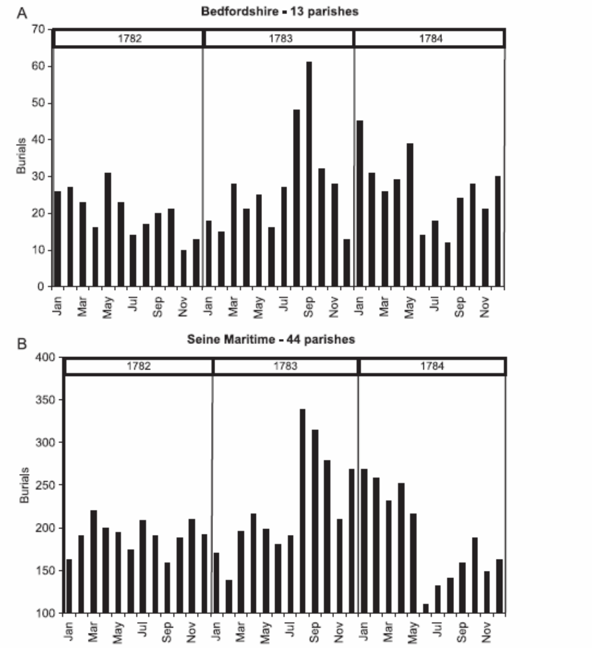

Fig. 4. Mortality 1782–1784 in (A) 13 Parishes in Bedfordshire, England and (B) 44 parishes in the Seine Maritime region, France.

4. Critical synergies

Through June and July 1783, the eruption released over 80 Tg of SO_2 into the atmosphere. The emitted sulphur generated a persistent acid fog which had a complex impact upon the environment including, extreme weather, acidification of still waters, acid damage to plants and ill health, disease and death. A key component of the severity of these events appears to be the concurrent atmospheric circulation patterns. Kington (1988) has produced a weather map for Europe for each day of the 1780s. Referring to 1783, it is clear that the most severe pollution events in Europe occurred when stable anti-cyclonic air masses drew gases and aerosols down to the surface from the upper troposphere, while these anti-cyclonic masses dominated atmospheric circulation, air pollution, with all its consequences was inevitable. It is clear from the comments of contemporary observers that this weather pattern was closely associated with the dry fog and the extreme environmental impacts. Stothers (1996) estimated that 6 Tg of acid material was delivered to the surface every 2 days; in essence, the dry fog was continually replaced and renewed from above, with the inevitable environmental consequences noted above. The combination of volcanic gases in the high troposphere/lower stratosphere and anticyclonic circulation patterns characterised by descending air masses is critical (see illustrations in Grattan and Brayshay, 1995; Thordarson and Self, 2001) and illustrates an essential synergy. While the upper troposphere is charged with volcanic gases, any anti-cyclonic air mass will draw these gases in and efficiently transport them to the surface. The very nature of such weather patterns is stability and persistence; hence, any area below such a descending air mass may receive an excess pollution burden for several days or weeks. Proximity to an active fissure eruption volcano is therefore not the only key to volcanic pollution impacts, stable anti-cyclonic air circulation masses are also key, and these will ensure that gases are transported great distances and concentrated near the surface, with the range of impacts described above.

The environmental impacts of the Laki Fissure eruption have not been equalled by any eruption since. In addition to the general cooling, which assessments of the climatic impact of volcanic activity may lead us to expect (Robock, 2000), repeated cool summers are apparent in the European instrumental records (Fig. 3). Stifling heat is also described everywhere by correspondents writing in those areas of Europe below the anti-cyclonic air mass. A general consensus accepts that this heating is likely to have been caused by the volcanic gases, but the mechanism by which this occurred is as yet unclear. The most severe environmental impacts of the Laki Fissure eruption appear not to have been the result of climate change, but rather the result of the deposition of acids and other volatiles in sufficient concentration to induce human illness and severe damage to plants across a huge area of Europe.

5. The Laki Fissure continental flood basalt

The following discussion is inevitably speculative, but it considers the likely range of environmental impacts that could be expected had the Laki Fissure eruption maintained its peak output for a whole year, and, in essence, resembled a single lava flow of a CFB episode, for instance the Roza flow of the Colombia River basalt group (Thordarson and Self, 1996). Several basic assumptions are made here to produce this scenario: (1) that 80 Tg of sulphur are released every 50 days throughout the year; (2) that the gases emitted are distributed between the troposphere and stratosphere on the 75–25% basis already established for the Laki Fissure output; (3) that the gases emitted were oxidised into an aerosol mass in the same ratio as those of the actual Laki eruption, i.e., 1:1.64.

The above assumptions allow the following broad estimates to be made: (1) in a single year, 576 Tg of sulphur gases could be emitted; (2) the gases could have been oxidised into approximately 945 Tg of aerosol; (3) that the stratospheric aerosol could be formed from 236 Tg H_2SO_4; (4) that the tropospheric aerosol mass could contain 708 Tg H_2SO_4.

5.1. Climate and weather

The estimates outlined above propose the formation of stratospheric aerosol mass of 236 Tg H_2SO_4, this is over four times the stratospheric aerosol loading of the Tambora eruption. At the very least, anomalous weather patterns including severe winters and cool summers in the Northern Hemisphere should be anticipated. A consistent reduction in average summer temperatures would reduce the latitudinal and altitudinal range of many plants and critical functions such as fruiting and reproduction could be severely disrupted. There is evidence that high latitude environments were drastically affected by the Laki eruption in 1783 and that in Alaska there was no summer in 1783, which resulted in a disaster for the Inuit inhabitants (Jacoby et al., 1999). Continued over several years, this phenomenon could inevitably result in permanent changes in plant and animal distribution. If average winter temperatures are also reduced over several years, then the beginning of Spring could be later and Autumn earlier. This would reduce the growing season and this again would affect critical processes for many plants including their ability to produce fruits with viable seeds.

5.2. Acid damage to the environment

A tropospheric aerosol mass of 708 Tg H_2SO_4 has a great potential to generate environmental change via deposition on plants and land surfaces. With the troposphere recharged with aerosols throughout the year, repeated episodes of sulphur deposition may be anticipated. The destruction of plants observed in June and July 1783 could be repeated throughout a year, and animals, including fish and insects, and plants would all be affected to a far greater degree. It may be expected that a wider area would be affected by the dry fog, that this would be more persistent, that the concentrations of volatiles in the aerosol would be greater and the pH of the aerosol be even lower. The following phenomena could be anticipated: intense impacts of acids at great distance from the source, recurrent environmental forcing, decreasing environmental tolerance, a reduction of biodiversity, the expansion of acid tolerant species, the removal of essential bases from acid soils and the acidification of poorly buffered inland waters.

In the plant kingdom, a wide range of processes would be severely affected including: growth and maturity; the retention of leaves and hence photosynthesis; flowering; fruit growth, retention and maturity; seed formation, growth and germination. All types of plants would be affected including colonisers such as Rumex and grasses, which stabilise fragile soils. Soils which evolve in cold, wet environments are poor in essential bases and vulnerable to very moderate acid deposition and climate change (Bull, 1991; Hudson, 1988). The scale of acid deposition following even minor Icelandic volcanic eruptions is on a scale, which may critically stress many of the soils in northern Scotland and other Boreal environments (Grattan and Gilbertson, 1994). An event of the magnitude described here could conceivably deposit sulphur in excess of the critical threshold for acid loading of soils across Europe. With the destruction of plants and the acidification of soils, the resistance of soils to erosion could be reduced and soil erosion and increased sediment transport in rivers may result.

6. Discussion

Severe though they actually were, had the Laki Fissure maintained its peak output for an entire year, the environmental consequences would have led to an environmental crisis. Rather than most of the damage to the environment being confined to a brief period between June and July, acid rain and aerosols would have been deposited repeatedly. Between June 8th 1783–June 8th 1784 stable high-pressure systems dominated the weather of Europe on 11 separate episodes totalling 147 days, during which volatile gases and aerosols could have been delivered to the surface. Assuming the intensity of each episode to be comparable to that which actually occurred in 1783, severe acid damage to the environment could be predicted on 10 further occasions with inevitable intense modification of ecosystems.

Taking the climatic and environmental modifications together, it is plain that a single CFB lava flow over a single year would be a powerful environmental forcing mechanism. It is clear from the actual events which occurred in 1783 that such volcanic activity may wield a direct influence on distant environments on at least a continental scale. This influence is severe and includes the impacts of extreme weather and climate plus acid deposition. Taking the impacts of these processes upon plants over several years, we may predict a severe reduction in their range and an impairment of their ability to reproduce themselves, there would be an inevitable further impact upon the animals which relied on them. The lesson which the Laki Fissure eruption may contribute to CFB studies is therefore one of sudden, extreme impacts of acid fallout and contamination over a wide area, which would be repeated throughout the life of the flood basalt eruption over many thousands of years. Inevitable in such a scenario critical environmental thresholds would be crossed, from which recovery would be limited and significant long term environmental change could ensue (Skiba et al., 1989; Smith et al., 1993).

Finally, what of the future? Global agricultural provision in our interdependent world is considered vulnerable to sudden global cooling (Engvild, 2003) and the risk to air travel by volcanic activity is already monitored and managed by the Volcanic Ash Advisory Centres (Vaacs), part of the global air-traffic control network. In addition, human health is already considered vulnerable to synergistic combinations of weather and poor air quality (Katsouyanni et al., 1993), seen most recently in Europe in the summer of 2003, and a wide range of terrestrial and aquatic ecosystems are vulnerable to acid deposition. Were the Laki Fissure eruption to occur today the implications for the European environment would be considerable. Volcanic gases would considerably enhance the anthropogenic air pollution already concentrated in major population centres, with potentially dire consequences for human health. As in 1783, we could anticipate acid damage, occasionally very severe, to plants across much of Europe and perhaps North America. Air travel from Europe to North America would be disrupted for months as aircraft were rerouted to avoid exposure to airborne acids and tephra. However, as in 1783, the modern world would no doubt absorb these pressures. A modern CFB scale event would inevitably present a problem on a much larger scale. Potentially long term climate change or repeated climate forcing, combined with repeated episodes of acid deposition and frequent formation of acid fogs could disrupt many features of modern life. In our interdependent modern world, with its reliance on cheaply available imported food, convenient air travel, and the provision of extensive social support and welfare systems which are ultimately financed by economic productivity, it is not difficult to envisage that the impact of a modern CFB would be catastrophic (cf. Rampino, 2002).

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